

## **Estimating Winds from Synthetic Aperture Radar under Typhoon Conditions**

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### **LONG-TERM GOALS**

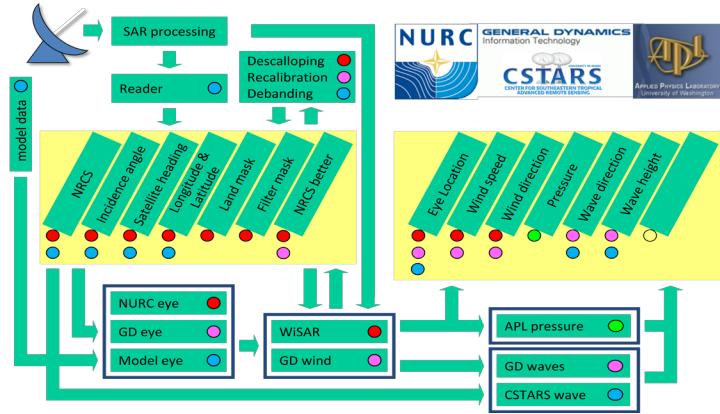
The Impacts of Typhoons on the Ocean in the Pacific (ITOP) program is a multi-national field campaign that aims to study the ocean response to typhoons in the western Pacific Ocean. The main goals are to understand the formation and dissipation of cold wakes and how ocean eddies affect typhoons. The NATO Undersea Research Centers (NURC) activities within ITOP are related to extracting high resolution wind fields as well as information on the tropical cyclones eye from synthetic aperture radar (SAR) data. This SAR derived information will be helping to better understand air-sea fluxes under extreme wind speeds and improve the knowledge and estimates of surface wave fields under typhoons as well as the typhoon forecasting.

### **OBJECTIVES**

NURC is part of the ITOP SAR Team working on extracting wind and wave information from satellite borne SAR data. One of the major objectives is the development and implementation of the SAR Typhoon Processing System (SARTyPS) for near real time processing of SAR data (Figure 1) at the the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) of the University of Miami. It is anticipated to incorporate the SAR-retrieved information into numerical models in particular with respect to tropical cyclone forecasting.

The main objectives for NURC within ITOP are the development of algorithms that are capable of extracting wind information as well as tropical cyclone eye information from SAR data in near real time and fully automated. The SAR activity within ITOP is a close cooperation with the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) of the University of Miami, General Dynamics Advanced Information Systems (GDAIS), the Applied Physics Laboratory (APL) of the University of Washington and the APL of the Johns Hopkins University (JHU).

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**Figure 1: Scheme of the SAR Typhoon Processing System (SARTyPS) being developed within ITOP. The modules marked with a red dot are being developed at NURC in close cooperation with the ITOP SAR Team.**

## APPROACH

For the retrieval of high resolution ocean surface wind fields from SAR under tropical cyclone (TC) conditions the WiSAR tool (Horstmann et al., 2002; Horstmann and Koch, 2005) developed at the Helmholtz Center Geesthacht, Germany (former GKSS Research Center), was extended for application to TC's.

Wind directions are extracted from wind-induced phenomena that are aligned in wind direction. The orientations of these features are derived by determining local gradients of the normalized radar cross section (NRCS). Therefore, the SAR image is sequentially smoothed and reduced to resolutions of 100, 200, and 400 m. From each of these smoothed images, local directions defined by the normal to the local gradient (to within a 180° ambiguity) are computed. Pixels associated to land, surface slicks, and strong rain, are masked and excluded from the analysis by considering land masks and several parameters retrieved from the SAR image (Koch, 2004). Within the extension of WiSAR for application to TC's we now have to pick the wind direction from all the retrieved local directions on the different available scales. Therefore, the algorithm searches for the most frequent directions in a predefined grid cell (typically 20 km) and picks the one, which is nearest to a circular direction around the center of the TC's eye. This approach is followed up to a range of 150 km from the TC's eye. For grid cells at a larger distance the nearest direction to its neighboring grid cell is selected (starting from the center of the TC's eye). To reduce the probability of outliers in the wind direction retrieval we merged the WiSAR retrieved wind directions with the results obtained from the approach of GDAIS. Their approach is also based on streaks, however, at larger scales (Wackerman et al., 2003) and has also been modified to the needs of TC's within ITOP (refer to ONR report by C. Wackerman, GDAIS).

Wind speeds are retrieved utilizing a geophysical model function (GMF) that describes the dependency of the normalized radar cross section (NRCS) on the local near-surface wind and imaging geometry. For C-band, VV-polarization, there are a number of popular model functions. The most commonly used is Cmod5 (Hersbach et al. 2007). Each of these GMFs is directly applicable for wind speed retrieval from C-band VV polarized SAR images (Monaldo et al., 2002; Horstmann et al. 2005). For wind speed retrieval from C-band SAR images acquired at HH-polarization, no similar well-developed GMF exists. To meet this deficiency a hybrid model function is used that consists of a C-

band polarization ratio (PR) and one of the prior mentioned GMF (Horstmann et al., 2002; Vachon and Dobson, 2002). For retrieval of wind speeds from SAR's operating at X-band, such as of the satellites TerraSAR-X and CosmoSkymed, we have developed an empirical GMF for both VV and HH polarized data (Thompson et al., 2011). To construct our empirical X-band GMF we have interpolated between the NRCS values from the well-tested GMFs at C- and Ku-band. We have used for C-band the Cmod5 and for the HH polarization version we have used the hybrid model function consisting of Cmod5 and the empirical PR developed by Mouche et al. (2005). For Ku-band VV and HH polarization we used the GMFs suggested by Wentz et al. (1984).

In addition to the high resolution wind fields we have developed a scheme to estimate the certainty of the retrieved wind speed at every SAR retrieved data point. This is in particular important as the error in wind speed is strongly dependent on the local wind speed and direction as well as the local incidence angle. Furthermore, we generate a mask identifying the regions that give NRCS's that are close or out of the definition range of the utilized GMF, these limitation also strongly depend on wind speed and wind direction as well as incidence angle. In case of Cmod5 they only occur at incidence angles below 35° in particular near to up- and down-wind direction with respect to the radar look.

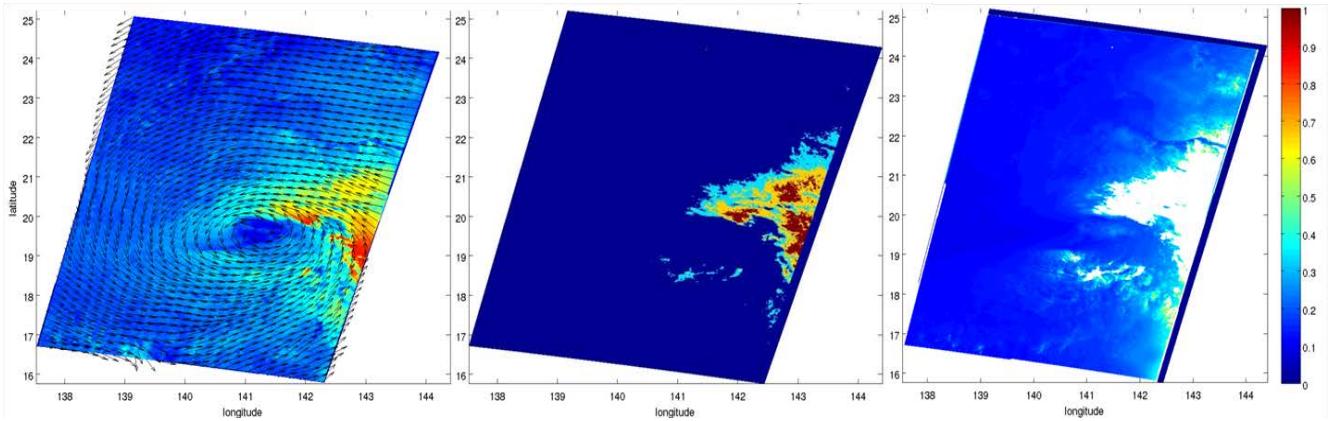
## WORK COMPLETED

We have completed the development of the wind retrieval scheme with respect to SAR's operating at C-band at both vertical and horizontal polarization and ingested our algorithms within the SARTyPS at CSTARS. The development of a geophysical model function for X-band wind speed retrieval has been undertaken as well as some preliminary comparisons of TerraSAR-X retrieved winds to model and *in situ* measurements under moderate wind situations (Thompson et al., 2011).

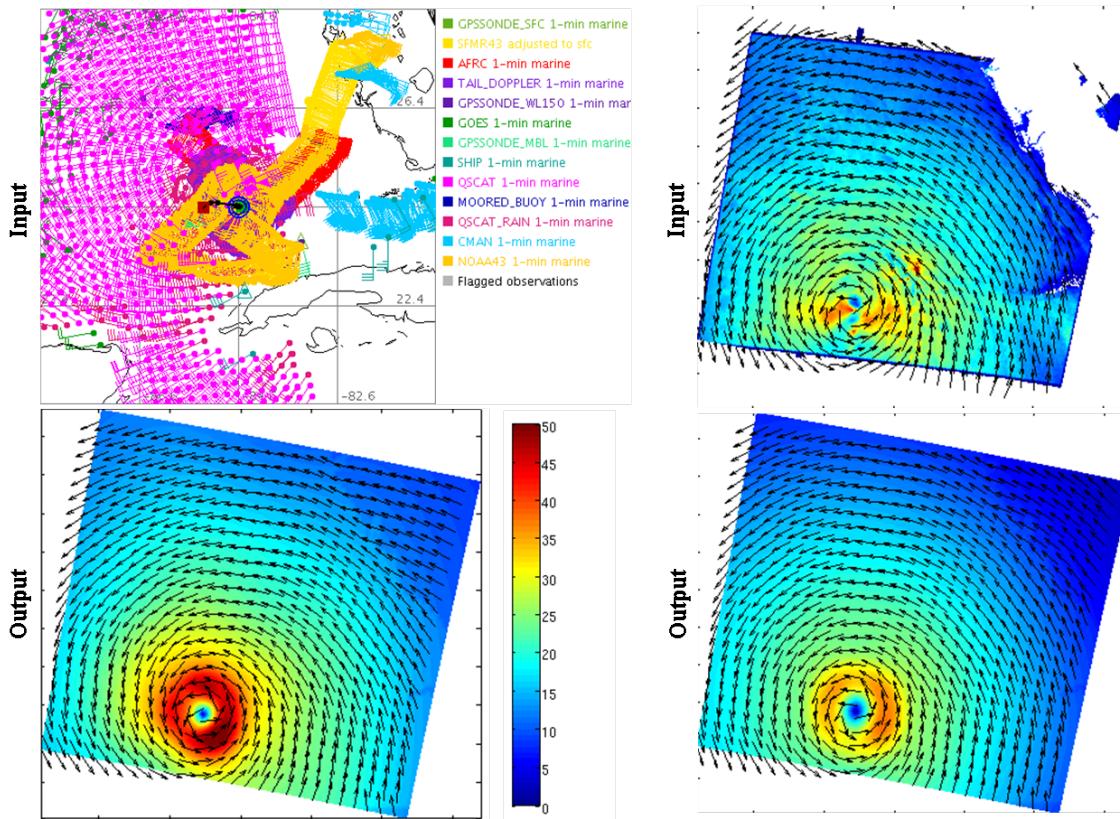
The wind products resulting from the approach of GDAIS have been merged with our results to reduce the probability of outliers in the wind direction retrieval of both approaches, resulting in a better overall SAR wind product. We have tested the C-band wind retrieval algorithms utilizing a historical data set of Radarsat-1 SAR images over tropical cyclones. All these SAR retrieved wind fields together with the error masks were made available to the the APL of the University of Washington, where they were ingested into their boundary layer model for retrieving pressure fields and improving the SAR retrieved wind fields (for results refer to ONR report by R. Foster APL).

Furthermore, we have applied the SAR wind retrieval scheme to the Radarsat-2 data collected during the ITOP experiment. In Figure 2 (left hand side) we depict the SAR retrieved wind field of Typhoon Malakas acquired during the ITOP experiment on the on 22. September 2010 at 2030 UTC. The center panel shows the Out of Definition mask (OD-mask), where the regions in yellow and red refer to NRCS values not defined in the Cmod5 GMF and regions in light blue indicate regions where the NRCS is close to (within 0.5 dB) the limits of the GMF. On the right hand side is an estimate of the Certainty mask (C-mask) of the SAR retrieved wind speeds ranging from certain (0) to uncertain (1). In the white color coded regions a certainty estimate cannot be retrieved.

The wind retrieval capabilities for X-band SAR data collected under tropical cyclone conditions have been been fully implemented with respect to TerraSAR-X data. The implementation of the retrieval scheme for CosmoSkymed data is ongoing. An in depth study concerning the calibration of CosmoSkymed data has just been started, which has indicated that post calibration steps have to be undertaken and implemented into SARTyPS.



**Figure 2:** SAR wind output resulting from the SARTyPS. The wind products were retrieved from the Radarsat-2 data acquired on the on 22. September 2010 at 2030 UTC in the Philippine Sea between Taiwan and Guam.

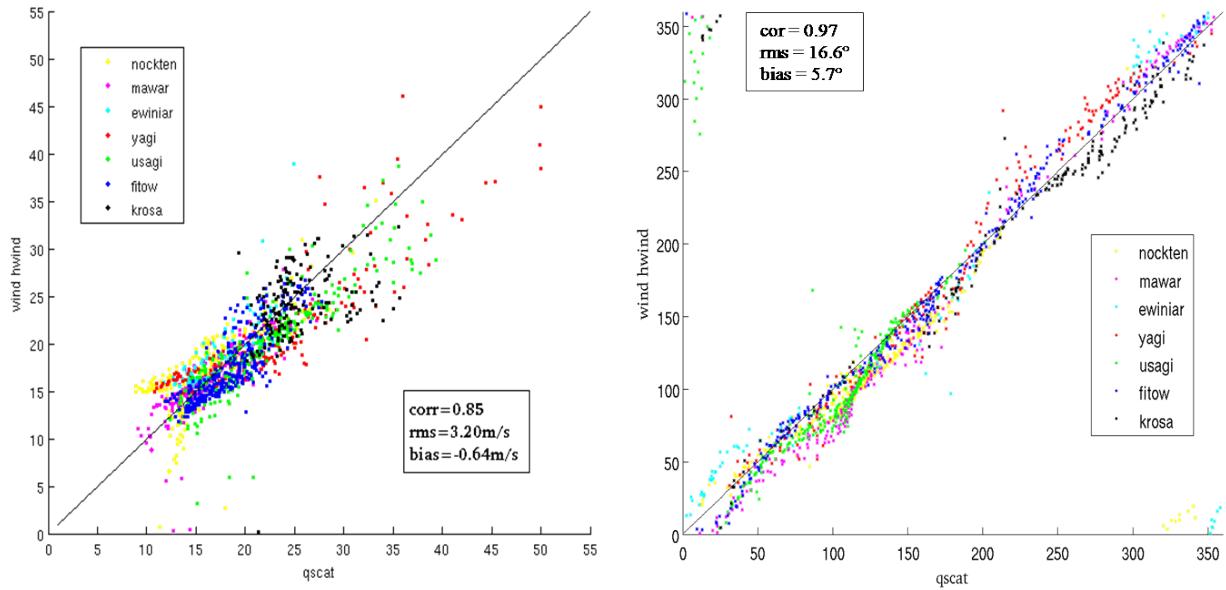


**Figure 3:** Results from NOAA's Hurricane Research Division Surface Wind Analysis System ( $H^*$ wind) when assimilating different wind inputs. Assimilation of sensors such as, Dropsondes, QuikSCAT winds, SFMR and others (top left panel) result in the wind field shown in the lower left panel. When only SAR retrieved winds (top right panel) are assimilated into  $H^*$ wind, the wind field results in the field depicted in the lower right panel.

Within an application study we have assimilated the SAR retrieved wind fields under consideration of the SAR retrieved OD-mask into NOAA's Hurricane Research Division Surface Wind Analysis System (H\*wind). H\*wind was developed for assimilating and synthesizing disparate observations into a consistent wind field (Powell et al. 1998). In Fig. 3 (left hand side) the wind field is depicted, which results from assimilating the available data within a time frame of 3 hours around the acquisition time of the Radarsat-2 SAR image. The assimilated data include measurements from the Stepped Frequency Microwave Radiometer (SFMR), GPS Dropsondes (from NOAA and AFRC flights) as well as other measurements depicted in Fig. 3 (upper left panel). The H\*wind results shown in Fig. 3 (lower right panel) were obtained by solely considering the SAR-retrieved wind field and the OD-masks. In case of assimilating the SAR data without consideration of the OD-masks, the resulting SAR assimilated H\*wind wind field would have been significantly overestimated. Note, that the lower wind speeds in the SAR wind field as well as in the SAR assimilated H\*wind output are partially due to the fact that SAR winds represent a 10 min. mean wind speed, while the typical wind input to H\*wind is given as a 1 min. maximum sustained wind speed, which results in an approximately 15% higher wind speed. Further investigation concerning the conversion of the 10 min. mean SAR wind speeds to 1 min. maximum sustained winds have to be undertaken in particular with respect to dependencies on spatial resolution.

## RESULTS

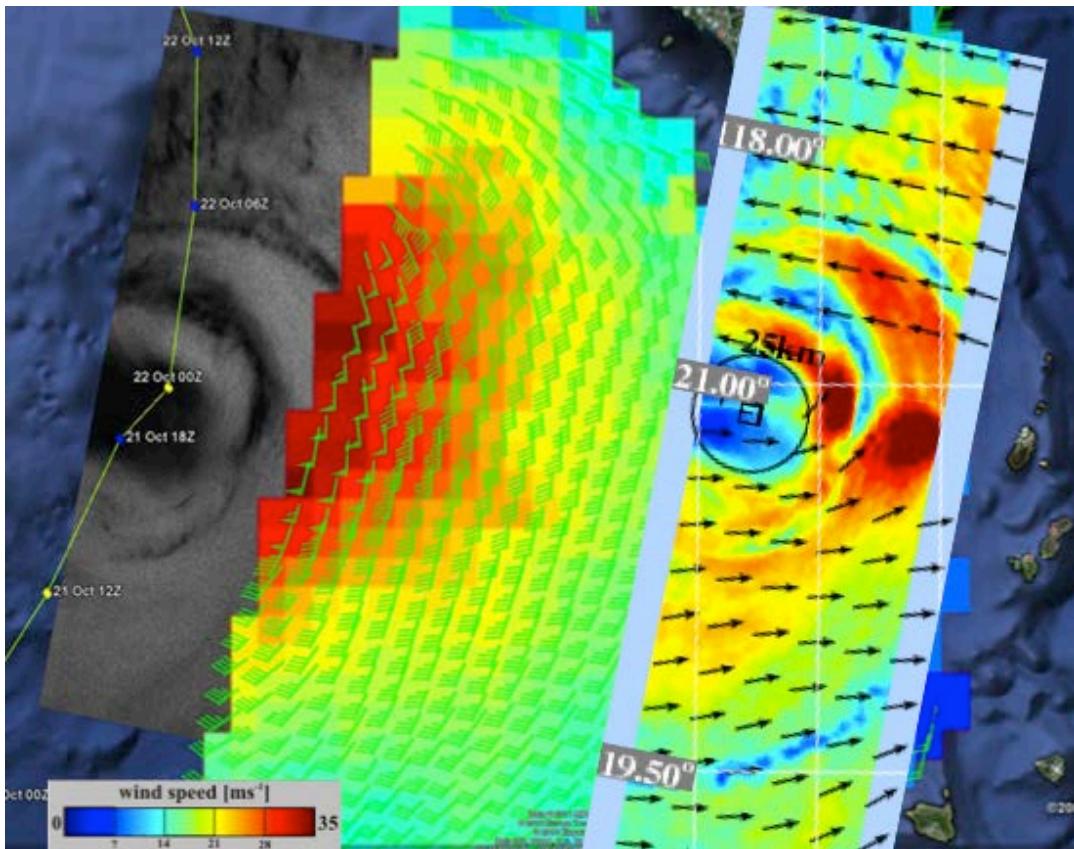
A historical data set of Radarsat-1 SAR images over typhoons in the Pacific and hurricanes in the Atlantic have been provided as part of the Radarsat-1 Hurricane Applications Project (RHAP). We selected a subset of these SAR data and co-located these to QuikSCAT data. Therefore, we have shifted the QuikSCAT results along the storm track to coincide with the SAR image acquisition time.



**Figure 4: Scatterplot showing the comparison of QuikSCAT winds to results from H\*wind after the assimilation of a SAR retrieved wind field. Wind speeds are shown on the left hand side and wind directions on the right hand side, respectively.**

We have compared our resulting SAR retrieved winds as well as the results of H\*WIND after assimilating the SAR wind fields under consideration of the SAR retrieved OD masks to the windfields retrieved from QuikSCAT. Within this comparison we excluded all QuikSCAT observations that had been flagged as rain contaminated. Unfortunately, this excludes a lot of QuikSCAT measurements near to the TC eye. The resulting root mean square (rms) error for the SAR retrieved winds was  $17.6^\circ$  in wind direction with a bias of  $6.4^\circ$  and a rms error of  $4.6 \text{ m/s}$  and a bias of  $-1.3 \text{ m/s}$ . Concerning the wind fields resulting from H\*WIND with an assimilated SAR wind field the rms was  $16.6^\circ$  in wind direction with a bias of  $5.7^\circ$  and a rms error of  $3.2 \text{ m/s}$  and a bias of  $-0.6 \text{ m/s}$  (Fig. 4). In both cases the SAR winds show less inflow and slightly under estimate the wind speeds.

The development of a geophysical model function for wind speeds retrieval from X-band operating at both vertical and horizontal polarization enables to retrieve high resolution wind fields from the X-band SAR missons such as TerraSAR-X and CosmoSkymed. In Figure 5 the preliminary results are shown of a wind field retrieved from the TerraSAR-X image acquired on the 21. October 2011 during the ITOP experiment. A qualitative comparison to results obtained from the ASCAT scatterometer shown in Figure 4 shows good agreement to the TerraSAR-X retrieved wind estimates, however, an in depth comparison and validation study of X-band wind retrieval has to still be undertaken.



**Figure 5: Preliminary results of TerraSAR-X retrieved high resolution wind fields of the SAR data acquired on the 21 Oct. 2010 during the ITOP experiment. The SAR image is shown on the rihght hand side with the supperimposed scatterometer retrieved wind field from ASCAT. The SAR retrieved wind field is depicted on right hand side.**

## IMPACT/APPLICATIONS

SAR retrieved wind fields are valuable additional information for the investigation and prediction of tropical cyclones. We have shown that one single SAR retrieved wind field assimilated solely into H\*WIND, achieves a very similar wind field as resulting from a large set of in situ and remote sensing data assimilated into H\*WIND. The development of the wind speed retrieval capability to X-band data enables to include additional SAR missions (TerraSAR-X and CosmoSkymed) meaning a shorter revisit time and therefore a larger temporal and spatial coverage.

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## PUBLICATIONS

Thompson, D.R., J. Horstmann, A. Mouche, N.S. Winstead, R. Sterner, and F.M. Monaldo,  
“Comparison of high-resolution wind fields extracted from TerraSAR-X SAR imagery with  
predictions from the WRF mesoscale model”, *J. Geophys. Res.*, in review 2011.